STARS AND PLANETS:

- THEIR FORMATION, CHARACTERISTICS AND DEVELOPMENT.

Close up image of prominences on the Sun

Earth and Space Science 2.6 (91192):

Demonstrate understanding of stars and planetary systems
External, 4 credits

Achievement	**Achievement with Merit**	**Achievement with Excellence**
Demonstrate understanding of stars and planetary systems	Demonstrate in-depth understanding of stars and planetary systems.	Demonstrate comprehensive understanding of stars and planetary systems

1. Achievement criteria:
Demonstrate understanding involves describing:
• characteristics of stars
• the position of stars on the Hertzsprung-Russel (HR) diagram
• stages in the birth, life and death of stars
• characteristics of planetary systems
• stages in the formation of planets and moons.

Demonstrate in-depth understanding involves explaining:
• how the characteristics of stars are linked to their position on the Hertzsprung-Russel (HR) diagram
• stages of the birth, life and death of stars
• stages in the formation of planets and moons.

Demonstrate comprehensive understanding involves explaining in detail:
• how characteristics of stars are linked to their position on the Hertzsprung-Russel (HR) diagram
• stages in the birth of stars with reference to energy changes
• stages in the formation of planets and moons.

2. A planetary system refers to one star, its orbiting planets and associated moons.

This Achievement Standard will form one of three papers in the Earth and Space Science Level 2 examination in the November NCEA External exams.

Our universe: wonder and awe

NGC 4414, a galaxy

Have you ever been away from city lights on a crystal-clear, moonless night?
The spectacle of countless stars spilled across the sky, like diamond dust on black velvet, would have been fairly common to our pre-urban ancestors. Today, those of us who are city dwellers only rarely get to see the sky like this because the 'black velvet' is rendered a muddy grey by city lights. When you do see the stars in all their glory, the impact can be all the greater because of its rarity. Stars have long fascinated humankind – we look for patterns and pictures among them, or try to predict the future by their apparent movement; we give them names and attach mystical significance to them. People have used the stars to navigate across the oceans or deserts, to work out the right time to plant their crops and to note the passing of the seasons. Changes and the night sky have been considered so portentous that they are thought to herald world-changing events – such as the birth of a Messiah.
One of the more obvious differences noted between 'stars' as observed by our ancestors was that some of them 'wandered' against a background of 'fixed stars'. These wanderers were called **planets**.

By the 17th Century some astronomers were beginning to suggest that stars were similar to our own Sun, but vastly further away. Copernicus, Galileo and others had already suggested that the Earth was not the centre of the Universe, and the Earth and other planets circled our Sun (rather than the Sun, stars and planets all circling the Earth). Although the Church forced Galileo to recant, the developing scientific understanding led to widespread recognition that the Church position couldn't possibly reconcile with observations. The fact that the Church could be so completely, and obviously, wrong dealt a fatal blow to religious authority and scientists and philosophers felt increasingly free to challenge orthodox thinking and religious doctrine. This ultimately led to the Age of Enlightenment, and a new and revolutionary understanding of the world based on reason rather than tradition.

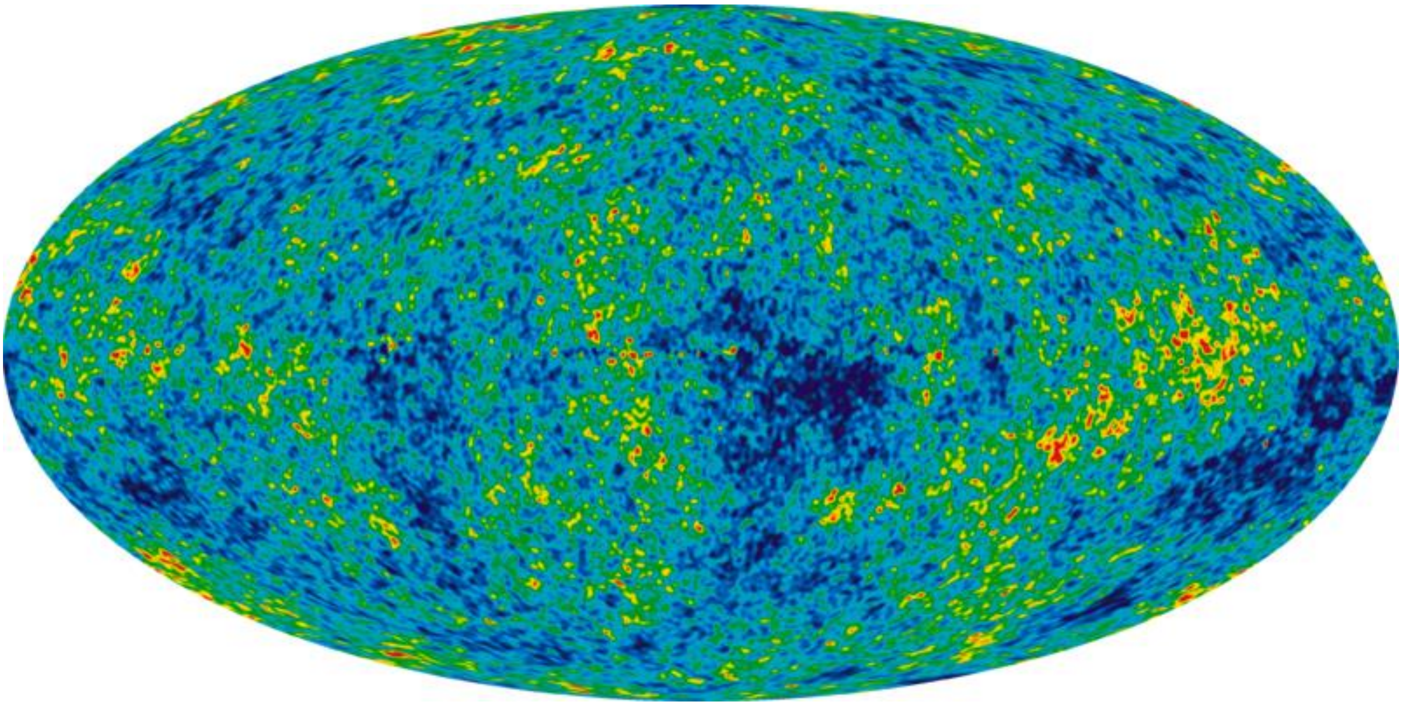
Since then, our understanding of our place in the Universe has changed utterly – Earth does not appear to occupy anyplace 'special' in the Universe, although the fact that we exist at all is pretty 'special' and extremely difficult for scientists to explain. Some resort to exotic theories to explain this, such as the idea that there is an infinite number of universes so one must exist where life is possible. What the difference is between this sort of idea and religious ones is a question for philosophers.

Our best understanding of our Universe today has come about as the result of observations by telescopes on Earth and in space, using wavelengths visible to the human eye and those visible only to machines. We can see many millions of stars in our own Milky Way galaxy and estimate their number (about 100 billion). We can see many other galaxies, from our near neighbour M31 in Andromeda to galaxies so far away they must have formed in the early days of the universe. The number of galaxies in the universe is also estimated to be about 100 billion, making the number of stars in the universe of the order of 10^{22} (fairly close to the number of atoms in a gram of hydrogen). We can observe their motion and use this to estimate their mass and other properties we can't directly 'see'.

Experiments with fusion and computer models give us ideas about the processes that go on in stars, the way galaxies and the whole Universe is evolving and why events such as supernovae and gamma-ray bursts occur. We can infer the existence of such unlikely objects as black holes or neutron stars, even though we can't directly observe them, from seeing how our observations match with mathematical models such as Einstein's General Theory of Relativity, quantum theory and the Standard Model of particle physics.

The Universe

Several lines of evidence suggest that the Universe began in a 'big bang' about 13.6 billion years ago (13,600 million years). We can still see the 'glow' of the early, hot universe in the form of the Cosmic Microwave Background (CMB). Although the radiation in the early universe was made of extremely short waves – what we would call gamma rays – space itself has expanded since then. The electromagnetic waves that made up the radiation in this early, hot universe have been 'stretched out' by the expansion of space in the universe, so that their original wavelength (of the order of femtometres) is now about 4 cm in length – microwaves. Everywhere we look in the sky we see these microwaves. The short wavelength radiation that once filled the whole universe has nowhere to go, so it is still there but shifted now into the microwave spectrum. A 'map' of this is shown below:



Small differences in the 'temperature' of this background are shown in the 360° sky panorama above, and give clues to the structure of the early Universe.

The Universe was originally very small, but expanded and cooled. Eventually, the highly energetic photons (radiation) of this early, hot, place cooled enough to condense into particles such as matter and antimatter. For an unknown reason, there was slightly more matter than antimatter (antiprotons and positrons) so that when the two annihilated each other some matter (protons and electrons) was left over. These cooled further and many protons and electrons bound together to form hydrogen and small amounts of a few other light elements (helium and lithium). Small differences in density caused this matter to clump, forming giant clouds, then galaxies and then stars. Stars were the nuclear factories in which the heavier elements were formed. Fortunately (for us) stars explode, so that these heavier elements were spread throughout the Universe, eventually condensing again to form second or third generation stars and their planets – including the Earth.

Since light travels at a finite speed (300,000 km per second, with no evidence that this has ever changed) an object further away must appear further 'back in time'. For example our closest galactic neighbour, M31 in Andromeda, is some 2 million light years away. This means the light left it to reach us 2 million years ago. We are not seeing it as it is now, but rather as it was 2 million years in our past.

If the Universe is about 13.6 billion years old, one would expect the furthest object that we can see to be this distance (in light years) away. In practice, it was some time after the Big Bang that objects we can 'see' formed. We can see this distance in either direction, so you would expect the 'visible universe' to be perhaps about 24 billion light years across. However, objects 'at the edge' of our vision would (in theory) be able to see that much further beyond them i.e. since we are 'nowhere special', we must lie on one edge of their 'visible universe'. This makes the 'visible Universe' some 48 billion light years across. What lies beyond? We don't know. Space may continue infinitely, even though there is no way we can possibly know anything events beyond this 'horizon'. Alternatively (and some cosmologists consider, more likely), the Universe may curve back on itself and what we could see if we looked far enough in the right direction (if it weren't for the time constraint) would eventually be ourselves. Cosmologists have been looking for patterns in the CMB that may indicate we are seeing the same thing in two different directions (as this would predict), but no definite candidates have yet emerged. This may mean that the Universe is infinite, or just that it is quite a bit bigger than our 48 billion light year horizon, or just that we haven't found the pattern yet. No doubt further discoveries will shed light on this.

1. What is the CMB and what does it tell us about the Universe?

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Astronomical distances

Everyday metres and kilometres really start to become unmanageable when you have to consider the various scales of the Universe. We can use scientific notation – for example the distance to Alpha Centauri is about 3.8×10^{16} m. However, this system is difficult for most people to visualize. Astronomers use a range of other units. The speed of light is the basis of one – the distance is given in terms of the distance light would travel in the stated time. One light second is 300,000 km. A light minute is 60 light seconds, a light hour is sixty light minutes and a light day 24 light hours. On this scale, Alpha Centauri is 4.7 light years (ly) away.

For **solar system** scales another unit is often used – the **astronomical unit (AU)**, which is the distance from the Sun to the Earth (about 8 light minutes or 150 million km). Jupiter is about 5.2 AU from the Sun, and Neptune about 30 AU out (4 light hours).

Another unit used by astronomers is the **parsec.** This unit is based on an angle to the Sun. It is about 3.2 light years. The 'absolute magnitude' of stars is based on how bright they would appear to be if they were a standardised distance of 10 parsecs from Earth (32 light years). Astronomers use standard multipliers for parsecs – kiloparsecs, megaparsecs and so on. On this scale the visible universe is a bit over one gigaparsec across.

2. If the Universe is 13.6 billion years old, how can it be more than 13.6 billion light years across?

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3. What filled the Universe in its earliest days? (and God said...)

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4. How was matter formed?

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5. (internet research question) The 'Anthropic Principle' is the notion that our Universe seems, against all odds, to have the conditions allowing the development of life (and therefore us). Why is this so odd? What alternatives to this idea are there?

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Section 2: Stars

Stars are made of gas, mostly hydrogen. They form from clouds of gas which collapse because of gravity. As the gas cloud collapses, it heats up. If the cloud is big enough, the centre heats up to 100 million degrees celsius, which is enough to start the process of nuclear fusion in its centre. This turns it into a star. There is considerable variation in types of stars in the night sky, which arises from two main factors about the star

1. How big it was to start with (i.e. its mass). This is because the larger a star, the larger the volume in the centre that is hot enough to initiate fusion, and therefore the more energy the star will be giving off. Because the volume rises with the **cube** of radius (i.e. a star with twice the radius has eight times the volume) this leads to two effects. Firstly, the surface area ony increases with the **square** of radius, so a star twice the radius will have eight times the volume and give off roughly 8 times as much energy, but this is radiated through only 4 times the area. This makes such massive stars hotter (we can tell temperature from the colour - see later section). Second, these large stars use up their hydrogen more quickly, so are not as long-lived as stars with less mass.
2. The age of the star: as alluded to above, stars eventually use up their hydrogen. When this happens, they undertake different types of fusion and this in turn causes them to change. For example, a star like our own Sun, when it has used up all its hydrogen, will become much hotter at the centre as it converts helium into other elements. This will cause it to swell up, and although it gives off quite a bit more energy the increase in surface area is even greater. This causes it to cool, and it will turn (for a while) into a red giant.

Because most stars spend most of their life using hydrogen for fusion, we call stars that are in this part of their life cycle **main sequence** stars. The majority of stars in the universe belong to this group. However, these stars will eventually leave the main sequence and different things will happen to them.

H-R Diagram

Since the temperature and brightness of a star depends on its size, it occurred to two astronmers (Ejnar Hertzsprung and Henry Norris Russell) to plot a graph of brightness against temperature; this graph is called the

How do we tell how far away stars are?

Close stars (<500 light years) can be measured directly from parallax. This means we measure the change in angle as we see the star from opposite sides of Earth's orbit around the Sun over 6 months (this give a triangle 300 million km at its base) – using trigonometry.

Certain pulsars (flashing stars) have a relationship between how fast they flash and how bright they are. We can measure the flashing rate of really distant stars, then, knowing their luminosity from the flash rate, work out the distance from their apparent brightness.

Using these as a measure it is fairly easy to then use the brightness of other stars to work out the distance to them.

These methods let astronomers work out that there is a relationship between the distance of a star and the 'red shift'. We can measure the distance to the most distant stars using this red shift, with a number called the 'Hubble Constant'.

This means that the distance to stars is worked out using a variety of different methods.

Even the most basic arithmetic tells us that nearby galaxies must be about a million times further away than nearby stars. The light from these objects left them millions of years ago. We can observe events such as supernovae happening in other galaxies.

This is a major difficulty for 'Young Earth' creationists, who think the Universe is less than ten thousand years old. They propose exotic explanations, such as –

- **The light was created 'in transit',** although this means that the events we observe in distant galaxies are completely fictitious (this is not in line with Catholic theology because it implies that 'God lies')
- **The speed of light has changed**; however a change this big would have fundamental implications in physics theory that no reputable physicist would entertain.

The definitions of 'Science' do not allow for the creation of unknowns (they are termed 'entities') like this. This is one of the reasons that so-called 'Creation Science' cannot be termed science at all – it does not fulfil the criteria by which 'science' is recognised as a discipline.

Hertzsprung-Russell diagram and an example is shown below. This one is a plot of 22,000 representative stars.

Some points about the HR diagram

- the **horizontal** (x-axis) is the **temperature** of the star, as determned by its 'colour'. Stars can be divided into different 'spectral classes' on the basis of this colour; for instance, our sun is a G star. On the graph above, hotter stars plot further to the **left** and cooler ones further to the **right**. A couple of different scales are used for this temperature scale, one shown at the top of the graph (temperature in kelvin) and one at the bottom (colour on the B-V scale). Different HR diagrams may show the scales in different places, but the all show the same pattern.
- The **vertical** axis is the **amount of light** the star gives off. This is plotted in two diffeent scales. On this graph, he scale on the left compares the amount of light to our own Sun i.e. a star that is 0.1 gives of 1/10 as much light as the Sun. On the right hand side is the same information given in terms of 'absolute magnitude' , which is a measure of the brightness they would appear if they were all a standard distance of 32.6 light years away. Once again, the position of the scales may vary for different diagrams but the information is the same. See later for a discussion of stellar magnitude.

The tables on the following two pages give the brightness and colour-temperature of various prominent or nearby stars. Plot this data onto the graph on page 10.

Left:

Two views of Saturn, as seen from the surface of its moon Titan.

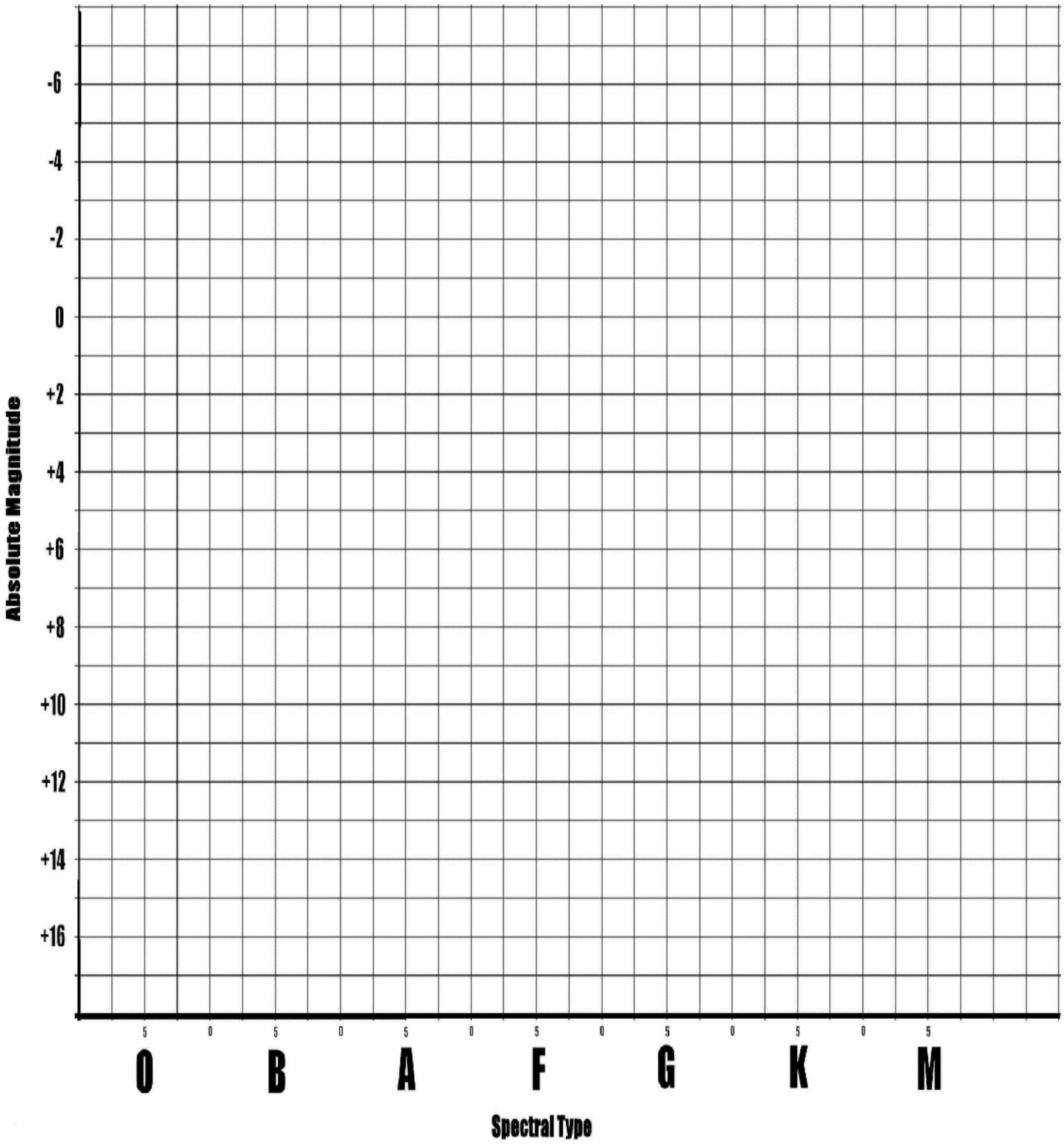
Titan is the only other body in our Solar System known to have liquid oceans, rain and similar phenomena. However, the liquid is not water but methane, ethane and similar substances. The hydrocarbon rich atmosphere is reddish in colour.

Brightest Stars from Earth

#	Common Name	Scientific Name	Const.	Distance (LY)	m	M	Spectral Class
A	Sirius	Alpha CMi	Cmi	8.6	-1.46	4.8	A1Vm
B	Canopus	Alpha Car	Car	74	-.72	-2.5	A9II
C	Rigil Kentaurus	Alpha Cen A	Cen	4.3	-.27	4.4	G2V+K1V
D	Arcturus	Alpha Boo	Boo	34	-.04	.2	K1.5IIIp
E	Vega	Alpha Lyr	Lyr	25	.03	.6	A0Va
F	Capella	Alpha Aur	Aur	41	.08	.4	G6III+ G2III
G	Rigel	Beta Ori	Ori	1400	.12	-8.1	B8Iae
H	Procyon	Alpha CMi	CMi	11.4	.38	2.6	F5IV-V
I	Achernar	Alpha Eri	Eri	69	.46	-1.3	B3Vap
J	Betelgeuse	Alpha Ori	Ori	1400	.5 v	-7.2	M2Iab
K	Hadar	Beta Can	Cen	320	.61 v	-4.4	B1III
L	Acrux	Alpha Cru	Cru	510	.76	-4.6	B0.5Iv+ B1Va
M	Altair	Alpha Aql	Aql	16	.77	2.3	A7Va
N	Aldebaran	Alpha Tau	Tau	60	.85 v	-.3	K5III
O	Antares	Alpha Sco	Sco	520	.96 v	-5.2	M1.5Iab
P	Spica	Alpha Vir	Vir	220	.98 v	-3.2	B1V
Q	Pollux	Beta Gem	Gem	40	1.14	.7	K0IIIb
R	Fomalhaut	Alpha PsA	PsA	22	1.16	2.0	A3Va
S	Becrux	Beta Cru	Cru	460	1.25 v	-4.7	B0.5III
T	Deneb	Alpha Cyg	Cyg	1500	1.25	-7.2	A2Ia
U	Regulus	Alpha Leo	Leo	69	1.35	-.3	B7Va
V	Adhara	Epsilon CMa	CMa	570	1.5	-4.8	B2II
W	Castor	Alpha Gem	Gem	49	1.57	.5	A1V+ A2V
X	Gacrux	Gamma Cru	Cru	120	1.63 v	-1.2	M3.5III
Y	Shaula	Lambda Sco	Sco	330	1.63 v	-3.5	B1.5IV

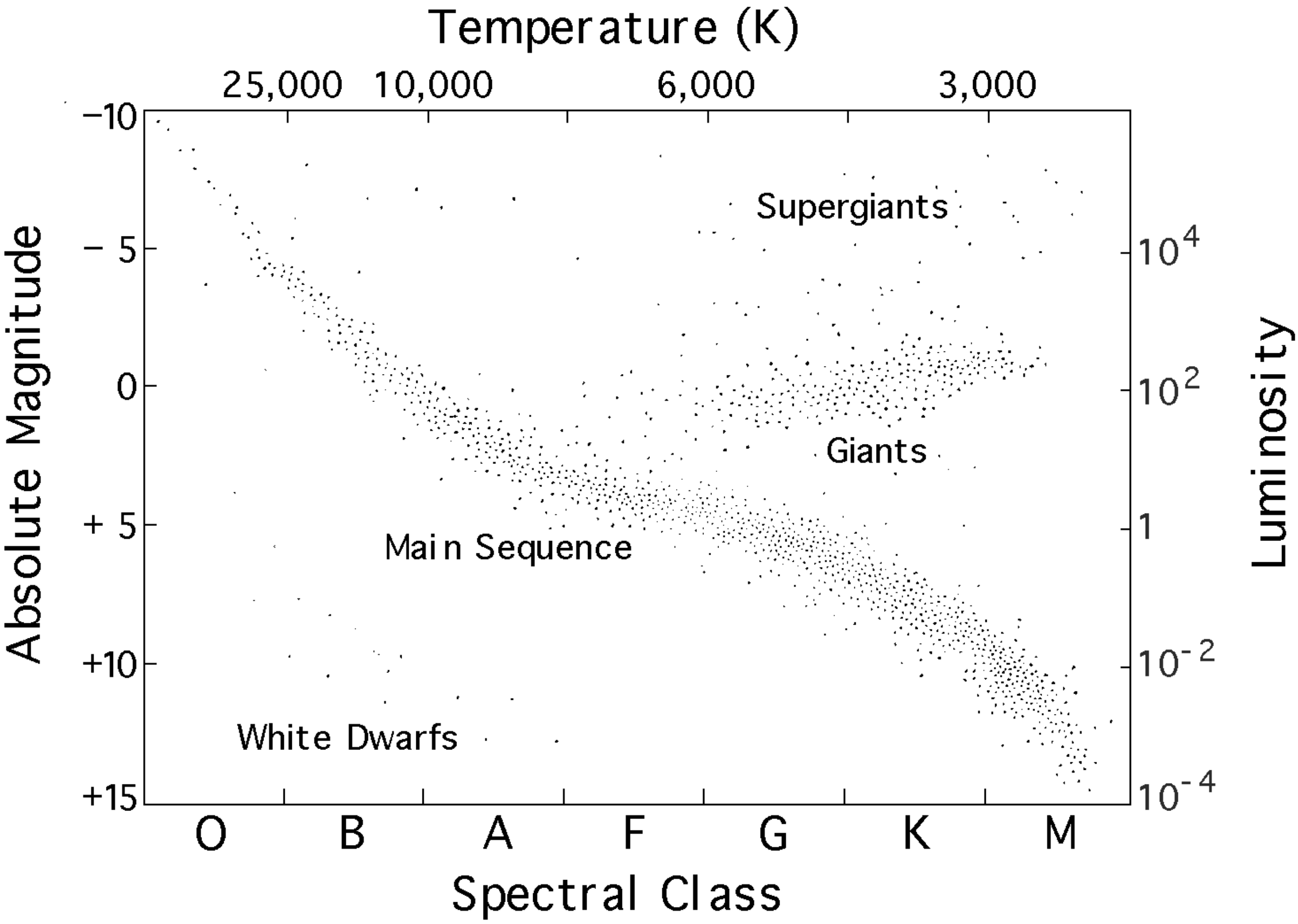
Stars Nearest Earth

#	Common Name	Scientific Name	Const.	Distance (LY)	m	M	Spectral Class
1	Proxima Centauri	V645 Cen	Cen	4.2	11.05 v	4.8	M5.5Vc
2	Rigil Kentaurus	Alpha Cen A	Cen	4.3	-.01	4.4	G2V
3		Alpha Cen B	Cen	4.3	1.33	5.7	K1V
4	Barnard's Star	Ross 858	Oph	6.0	9.54	13.2	M3.8V
5	Wolf 359	CN Leo	Leo	7.7	13.5 v	16.7	M5.8Vc
6	Lalande 21185	BD+36 2147	UMa	8.2	7.5	10.5	M2.1Vc
7	Luyten 726-8A	UV Cet A	Cet	8.4	12.5 v	15.5	M5.6Vc
8	Luyten 726-8B	UV Cet B	Cet	8.4	13.0 v	16.0	M5.6Vc
9	Sirius A	Alpha CMa A	CMa	8.6	-1.46	1.4	A1Vm
10	Sirius B	Alpha CMa B	CMa	8.6	8.3	11.2	DA
11		Ross 154	Sgr	9.4	10.45	13.1	M3.6Vc
12		Ross 248	And	10.4	12.29	14.8	M4.9Vc
13	Epsilon Eridani	Epsilon Eri	Eri	10.8	3.73	6.1	K2Vc
14		Ross 128	Vir	10.9	11.1	13.5	M4.1V
15	61 Cygni A	61 Cyg A	Cg	11.1	5.2 v	7.6	K3.5Vc
16	61 Cygni B	61 Cyg B	Cyg	11.1	6.0	8.4	K4.7Vc
17		Epsilon Ind	Ind	11.2	4.68	7.0	K3Vc
18	Groombridge 34	BD +43 44 A	And	11.2	8.08	10.4	M1.3Vc
19		BD +43 44 B	And	11.2	11.06	13.4	M3.8Vc
20		Luyten 789-6	Aqr	11.2	12.18	14.5	M6
21	Procyon A	Alpha Cmi A	CMi	11.4	.38	2.6	F5IV-V
22	Procyon B	Alpha Cmi B	CM1	11.4	10.7	13.0	DF
23		BD +59 1915 A	Dra	11.6	8.9	11.2	M3.0V
24		BD +59 1915 B	Dra	11.6	9.69	11.9	M3.5V
25		CoD -36 15693	Gru	11.7	7.35	9.6	M1.3Vc



-6
-4
-2
0
+2
+4
+6
+8
+10
+12
+14
+16
Absolute Magnitude
5 0 5 0 5 0 5 0 5 0 5 0 5
O B A F G K M
Spectral Type

A HR diagram generated by computer is shown below:



When you do this with a representative population of stars, you find that the stars don't plot randomly all over the graph. Instead, they plot into distinct areas as seen in the diagram above.The vast majority of stars fall into the line of the main sequence, because this is where they spend most of their life. White dwarfs are what is left of certain stars at the end of their life and red giants are one of the types created when stars leave the main sequence. We will look in more detail at these in a later section.

Characteristics of stars (as mentioned in the Achievement Standard)

Colour: the colour of a star depends on the surface temperature, with red stars being the coolest and blue-white the hottest. You would be expected to work out the temperature from a HR diagram but you do not need to memorize them. Colours are grouped into **spectral type** (on the top of the HR diagram);

- **O:** a rvery **rare, very massive and very bright star. Most of the output is ultraviolet**
- **B: blue stars, very bright and quite massive. The brighter Pleiades are an example.**
- **A and F: bright blue white stars, a bit more massive than our own Sun. Sirius is an example. These are quite common.**
- **G: this is the class our own Sun belongs to. Sometimes termed 'yellow' stars**
- **K: these are slightly orange stars, making them a bit cooler than the Sun. Some are giants and some main sequence smaller stars.**
- **M: red stars. Red dwarfs are small, long lived and very numerous. Red giants are a phase** many stars on the main sequence go through.

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Luminosity: this means how much light the star gives off; it is usually in terms of how many times brighter or dimmer

than our Sun the star is. The actual brightness of the star as seen from Earth is called its apparent magnitude and depends on both luminosity and distance.
Mass: Red Dwarfs are smaller than our own Sun; Red Giants and White Dwarfs are about the size of our own Sun. This is because all main sequence stars go through the RG and WD stage eventually. Stars at the upper left of the main sequence - classes A and B - are many times more massive than our Sun. We will look in more detail at these types and the reasons for them when we look at stellar life cycles.

1. Briefly describe the relationship between star colour and temperature.

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2. Characterise each of these star types. Give one or more examples of each.

Red dwarf:...

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Brown dwarf ....

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Yellow or orange dwarf ....

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Red Giant ....

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Bright (blue or white) star: ....

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Bright giant...

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3. A giant star is not always a massive star. Explain......................................

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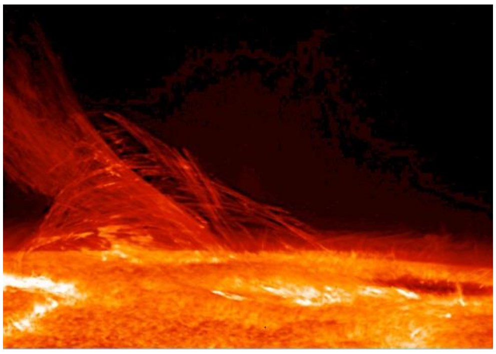
Stellar Fusion - where do stars get their energy from?


'Flames' are really streams of gas

Although stars look like they are burning, and sometimes we even say they are 'burning' hydrogen, they do not burn like a chemical fire. Stars get their energy from a process called nuclear **fusion**, in which the nuclei of light atoms such as hydrogen join together to make heavier elements. The 'flames' on the sun are really streams of hot gas following magnetic field lines.

Nuclear fusion is a process where atomic nuclei join together under extreme heat and pressure to form heavier nuclei. When light elements fuse to form other elements which are still lighter than iron (number 27 on the periodic table), fusion gives off energy (it is *exothermic*). This only happens deep inside the star, but the energy finds its way to the surface via convection, conduction and radiation and is eventually radiated away into space at the surface. Convection cells and magnetic effects look superficially like flames when this happens.

Fusion of any elements to form nuclei whch are **heavier than iron** uses up energy (it is *endothermic).* These nuclear reactions only happen during extreme events such as supernova explosions, and it is during these events that such heavy elements (gold, lead, tungsten, uranium and so on) are formed. We will look at this process later. For these

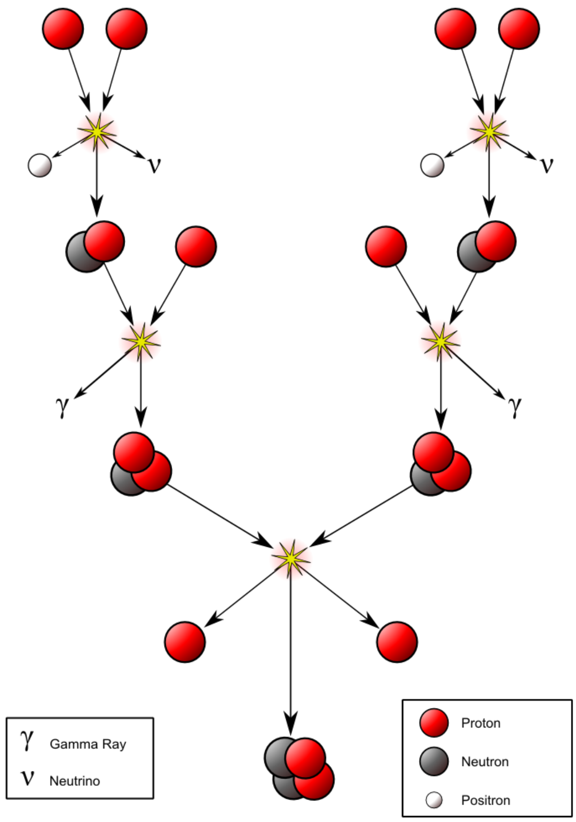
heavy elements, it is **fission** which is the exothermic process, although not all heavy elements will undergo spontaneous fission. Some do though, and give off energy,which is how our nuclear power stations work.

How does fusion occur?

Atomic nuclei contain protons and neutrons. The protons, being positively charged, repel each other with electrostatic force. Within an individual nucleus this repulsion is counteracted by a very powerful but short-range force caused by the exchange of particles called *gluons*. The holding-together against the strong repulsion results in the nucleus having potential energy which is called the nuclear binding energy. It is changes in this nuclear potential energy which power nuclear reactions, just as changes in the potential energy of electrons power chemical reactions. The nuclear binding energy is very large compared to electron energy levels, which is why nuclear power gives off so much energy for a given mass of fuel compared to chemical energy sources (e.g. 1 kg of uranium gives the same amount of energy as several thousand tonnes of coal).

For nuclear fusion to occur, the protons have to be brought close enough together so that the short-range nuclear binding force can overcome electrostatic force. In a star, this happens because of :

- extremely high temperatures, which initally arise from gravitational compression and
- extremely high pressures, resulting from the incredible gravity



Proton-Proton fusion (Wiki commons)

A star will only begin the process of fusion if it is big enough to create temperatures and pressures sufficient to do this. The only way we humans have been able to mimic these forces with out technology to any degree sufficient to release a lot of energy to date has been in a hydrogen bomb.(which uses a conventional fission bomb to create the temperatures sufficient to initiate fusion), although scientists are trying to mimic the conditions inside a star to create atomic fusion reactors. The fact that temperatures and pressures are so high is the reason that economic fusion has still not been achieved.

The diagram on the left shows the stages in the simplest form of fusion in true stars: proton-proton (hydrogen) fusion. You do not need to know the details of this process, but you do need to know that this is the form of fusion that occurs while a star is on the main sequence. As you can see, it forms helium. Later on in the star's life, when it runs out of hydrogen, the helium will be involved in other forms of fusion to make heavier elements.

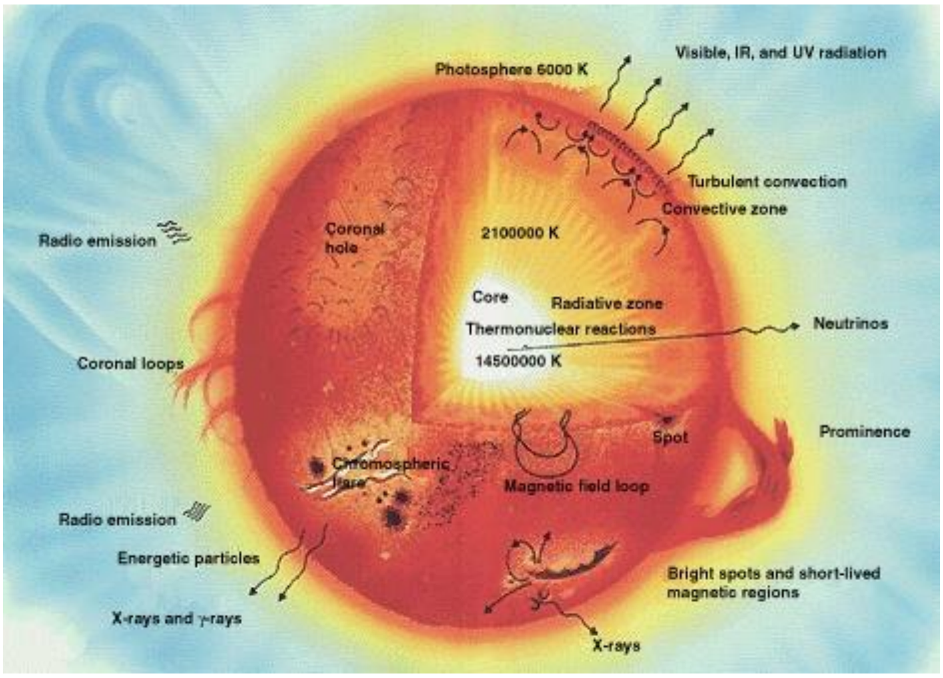
A type of star which is too small to initiate proton-proton fusion can give off some energy due to other types of fusion, and is called a Brown Dwarf star.

Processes in the star

Stars get their energy from fusion, as described above. However, this only takes place in the very core of the star. The energy makes its way to the surface, taking many years to get there.

The matter inside a star is in a state called plasma, in which the protons and electrons that make up ordinary atoms have become separated.

The plasma behaves something like a gas at the surface of a star, but under the extreme heat and pressure deeper inside the star it has more unusual properties. You do not need to know much detail about this. However, one important factor for our understanding of the life cycle of stars is that the energy making its way out in the radiative zone applies 'pressure' to the plasma, stopping the immense gravity from collapsing it. It is when this process stops working in certain types of stars that they explode. The other interesting thing is that the movement of plasma in a star causes immense magnetic fields. It is these which cause many of the features we see a the surface such as prominences.



Structure of a star (NASA)

1. Explain how stars get their energy ....

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2. Explain where the energy is produced and how it gets to the surface. ...

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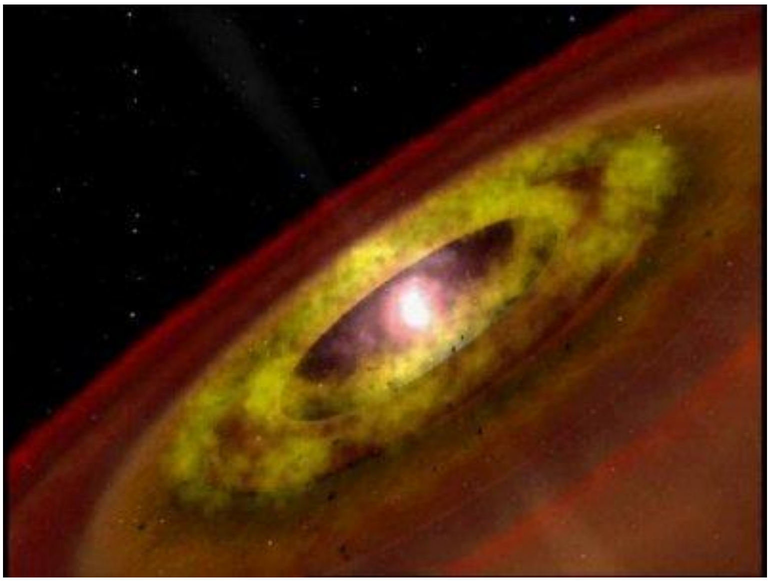
Life cycle of a star

The life cycle of a star depends quite a lot on its size. We will look at smaller stars first, which spend most of their life on the main sequence.

Collapse of gas clouds: the universe has many clouds of gas. They are not uniform, and areas of denser gas have more gravity which leads to denser gas and so on. Part or all of the gas cloud will therefore collapse, heating up as it goes, to form a **protostar.** Because the collapsing gas is usually rotating, it forms into a disk. This heats up, creating a type of star called a T-tauri star. The heating up is thought to blow away a lot of extra gas and may be important in forming planets. At this stage it is not hot enough to fuse hydrogen, although other fusion reactions may occur. This stage can last for thousands of years



drawing of T-tauri star (Wiki)

.When the temperature of the stellar core reaches 10 million kelvin, hydrogen (proton-proton) fusion begins. The process of balancing gravitational contraction begins and the star reaches a stable state after a short while. The star will now sit somewhere on the main sequence of the HR diagram.

What happens next depends on the size of the star.

Red Dwarfs: these smallest of the stars only fuse their hydrogen at a very slow rate. They will stay on the main sequence for tens or hundreds of billions of years. As the universe is presently about 13.6 billion years old, no red dwarfs have left the main sequence yet, and predictions about what will happen to them are based on models.

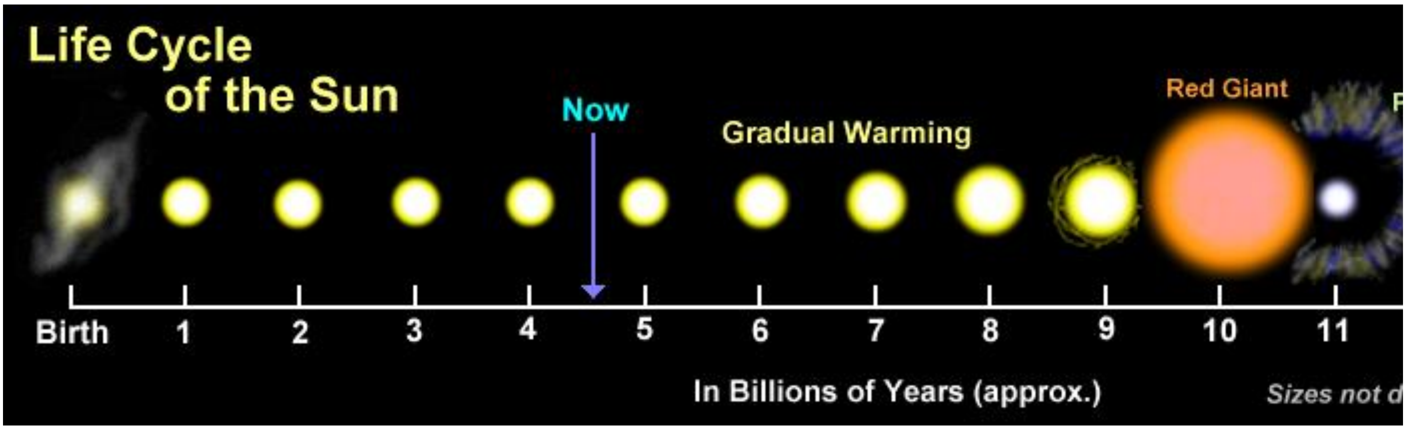
The smallest a red dwarf can be is about 0.075 stellar masses. Depending on their mass, they may begin to fuse heavier elements (but not all the way up to iron) which will make them get hotter; this will move their colour towards blue. The universe is not yet old enough to have 'blue dwarfs', so their existence is based on computer models.

When the fusion process runs out, these dwarfs will collapse and undergo gravitational heating. They will be white dwarfs composed of oxygen, silicon or similar elements. Eventually they will radiate their residual heat away and cool into black dwarfs. This may take trillions of years.

Mid size stars: Stars greater than a certain size transfer heat by radiation rather than convection in the core of the star. This results in less mixing, so helium that is formed sinks into the core and builds up because it is greater in density. The denser core is prevented from collapsing by electron degeneracy pressure, but the higher gravity above it causes hydrogen to fuse faster, increasing the luminosity (and moving it upwards on the HR diagram). It also expands, causing the outer layers to cool and become more red (causing it to move to the right on the HR diagram). Eventually, helium fusion will start in the core when the temperature reaches the 100 million degrees needed for this. The actual effect of this on the star depends on its size; there may be a 'helium flash' when helium fusion starts, or it may start quietly.

Helium fusion is not as stable as hydrogen fusion, so the star may pulsate with bursts of extra energy output. This may be sufficient to throw off part of the outer layer of the star to form a planetary nebula.

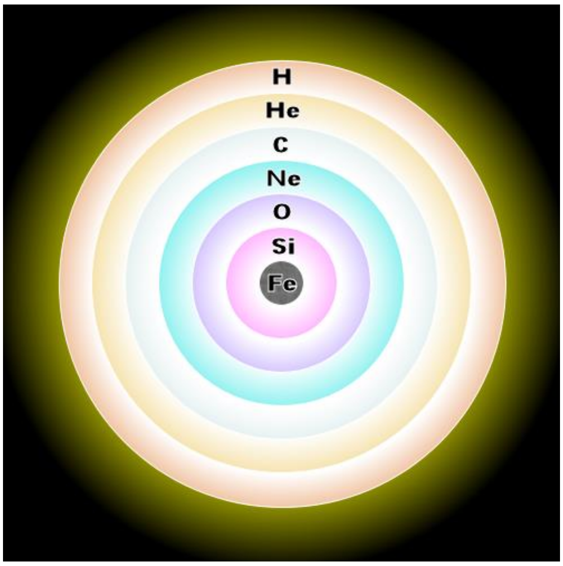
As the star continues to age, it will fuse succesively heavier elements such as carbon and nitrogen. However, the total energy output drops (moving it downwards on the HR diagram), and the star contracts. This in turn makes it heat up, so it turns white and its position on fhe H-R diagram moves to the left. It has become a white dwarf.



Life cycle of the Sun (Wikimedia commons)

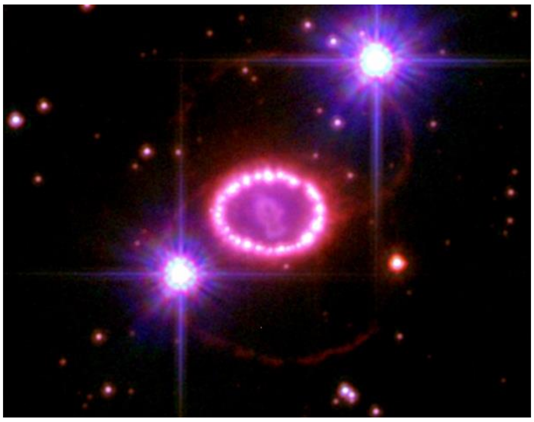
Large stars

High mass stars contain a greater volume within them at the core where it is hot enough to fuse hydrogen into helium. As a result, they burn through their hydrogen much more quickly than small or mid-sized stars. Heat transfer in the core is by radiation, so the helium produced sinks to the centre rather than is mixed up. Its density is higher than hydrogen, and it heats up, eventually causing helium fusion to produce carbon. A similar process occurs with carbon to form neon, neon to form oxygen and so on. The star builds up a layered structure as shown on the right.



Shells of progressively heavier elements in a mid-sized star in its Red Giant phase.

Nuclear fusion cannot yield energy for elements heavier than iron, so the series stops there (if the star is heavy enough). The iron core produces no energy, and although it is very dense, it is still 'normal' matter, in that it consists of protons and electrons. They are held apart by special properties of quantum physics called **electron degenerancy pressure.** Once this core exceeds a certain size (1.4 times the mass of our Sun, called the Chandrasekhar limit) , the gravitational force is large enough to overcome this pressure. The electrons are pushed into the protons, and form neutrons. The core undergoes a drastic reduction in volume - it collapses. This is the beginning of a **supernova** explosion or, correctly, a Type II supernova (there are other things that can cause stars to explode).



Expanding gas cloud around a supernova remnant

What happens in a supernova: The first stage of the supernova is caused by the generation of an iron core by nuclear fusion, which grows until it reaches about 1.4 times the mass of our Sun (1.4 solar masses). The gravity is then too strong for the 'pressure' holding electrons and protons apart, and they combine. The core of the star implodes, shrinking rapidly and heating up. this generates huge numbers of neutrons and neutrinos (neutrinos are a bit like electrons but have no charge).

These particles contribute to a sudden heating of the outer part of the star.

The imploding core reaches a maximum density, caused by short range forces betwen the neutrons, and 'bounces' outwards. The shock wave this causes actually makes parts of the rest of the star detach and be 'blown' out into space as an expanding cloud of gas - picture on left (20 years after the explosion)

The huge temperatures generated cause fusion reactions that use up, rather than create, energy. These fusion reactions create elements heavier than iron - all the elements from number 27 upwards on the periodic table. This is how we know that our own Earth and Sun contain material from a former supernova explosion - because these elements are present on Earth. Some of the newly created elements are radioactive, and it is from the decay of these that we can date that supernove. Current data suggests it happened about 8 billion years ago.
The stellar core formed during the supernova will remain behind. If the star that exploded is less than about 20 solar masses, it will form a neutron star. If it is more than this, it will form a black hole.
Full circle: the expanding cloud of gas continues its journey out into space, expanding and cooling. Eventually, the material will be thinly dispersed and will be incorporated into the nebulae and molecular clouds that float between the stars. The shock wave of the explosion will stir 'eddies' and currents in these clouds, starting off the process of gravitational collapse. Eventually, new stars will form incorporating the debris of the old one.

1. Describe the life cycle of each of the following star types:

Red dwarf...

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Yellow or orange dwarf ....

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Large star...

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2. Explain how a type II supernova occurs

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3. Describe neutron stars and black holes, and explain what factors determine which one is formed after a supernova.

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4. What is a T-Tauri star and what is its role in star formation?

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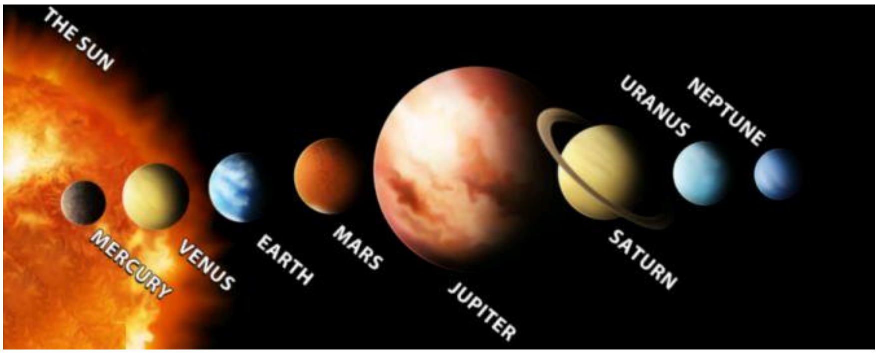
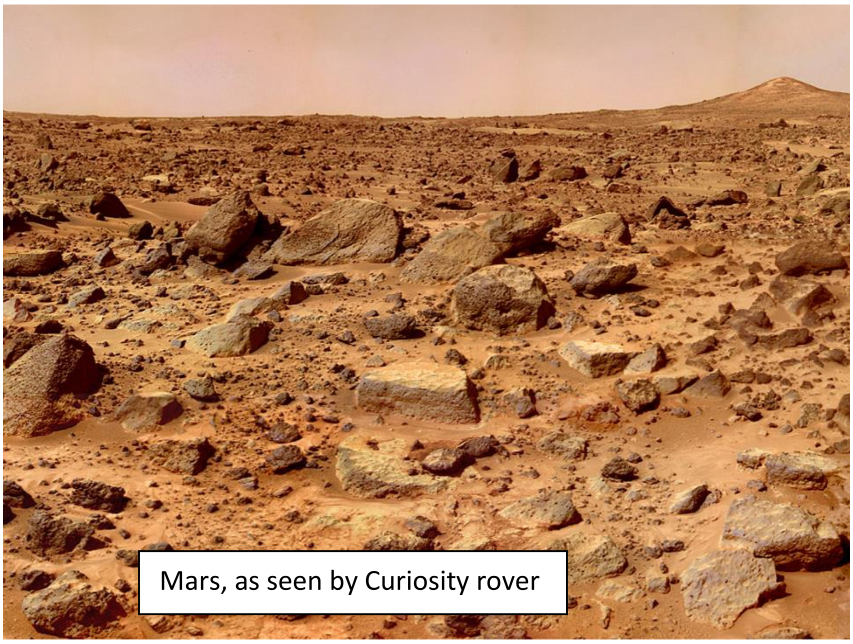
The formation of planets



Although it was known for all of the 20th century that our Sun is a star, generally similar to other stars, no planets outside our own solar system had been observed. Did other stars have planets? Most astronomers thought they did, but it was uncertain how typical our system is compared to other stellar systems.
An early question was whether the planets were formed at the same time as, and from the same material that formed, the Sun. Several lines of evidence suggested that this was so:

1. The planets all orbit the Sun in the same direction as the Sun rotates. If they had been 'captured' by our Sun's gravity from bodies wandering between the stars, one would expect their direction of orbit to be random (and the orbits to be much more eccentric i.e. less circular).
2. The eight planets (we will consider Pluto as a 'dwarf planet', not a true planet), all orbit very close to the same plane. This plane is called the ecliptic. This would be expected if both the Sun and the planets were formed from an originally rotating body of gas and dust, since gravity would eventually pull such a rotating body into a disc (centrifugal force in the plane perpendicular to the axis of rotation counteracts gravitational attraction in that direction, causing such a rotating body to 'bulge' at its equator. If the rotation is sufficiently large compared to gravity, this forms a disc; otherwise it will form a sphere flattened at the poles).
3. The ecliptic is perpendicular to the Sun's own axis of rotation; most planets axes of rotation are also close to perpendicular to the ecliptic (although they vary more than that of the Sun), suggesting a common origin.
4. Although the chemical composition of the planets differs from that of the Sun, the ratios of different isotopes of the various elements present are broadly similar. This is what would be expected if the Sun and the planets were formed from the same source of matter.

It was therefore thought that the planets had condensed from the same proto-stellar cloud of matter that formed the Sun. However, any theory of planetary formation had to account for some particular observations.

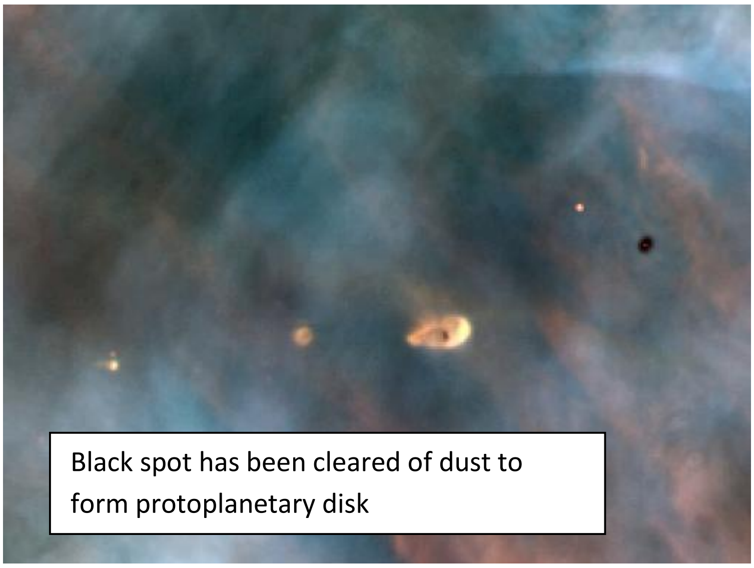

Mars, as seen by Curiosity rover

1. The planets can be divided into two groups of four: the four inner 'rocky' planets (Mercury, Venus, Earth and Mars) and the four outer 'gas giants' (Jupiter, Saturn, Uranus and Neptune). There is a very distinct difference in composition between these two sets of planets, although in the late 20th century it became clear that the gas giants all have 'rocky' cores similar to the inner planets. Thus the major difference between the two sets of planets is the presence or absence of a thick, hydrogen-dominated atmosphere (elements and compounds termed volatiles) which the four outer planets possess but the four inner planets do not.
2. There are a large number of smaller bodies orbiting in the Solar System. These are broadly categorised into two sets: rocky ones (asteroids), made of metals and silicates with minor volatiles, and icy ones composed

mostly of volatiles. Many of the rocky ones orbit between Mars and Jupiter, a zone known as the 'asteroid belt'; however, they are found all over the inner system. A large number of icy bodies orbit beyond the outermost planet (Neptune) in a zone known as the Kuiper Belt, and are known as Kuiper Belt Objects or KBOs. Pluto is now considered to be a KBO, and is the only one whose orbit regularly crosses that of Neptune. However, it is now known that at least half a dozen other Pluto-sized KBOs orbit a bit further out (the actual number is very uncertain as they are very hard to detect). These objects, and Pluto also, are not as strongly aligned into the ecliptic as are the planets (the fact that Pluto does not orbit in the ecliptic is one reason it is not considered to be a true planet). Non-planetary objects large enough for their own gravity to pull them into a spherical shape, but which are not moons, are termed dwarf planets.

3. The outer planets all have satellites which are icy, or display a mix of icy/rocky characteristics. Of the inner planets, only Earth has a significant satellite (Mars has two small moons, but they differ substantially from most other moons in the Solar System; computer modelling suggests that one of them will eventually either crash into Mars or break up into a ring). Earth's Moon is generally similar to the other rocky planets. Some of the larger moons in the outer system seem to have rocky cores.
4. At the fringes of the Solar System is a shell of widely scattered 'snowballs' known as the Oort Cloud. These are composed of ices of frozen gases, including water, methane, ammonia, carbon monoxide and hydrogen cyanide. It extends out to about 1 light year. It is where most 'new' comets come from (periodic comets, like Halley's Comet, originate much further in, nearer the Kuiper Belt).
5. Planets which don't have an 'active' surface, and which therefore preserve feature from the early days of the Solar System, are heavily cratered. This suggests that in the early days of the Solar System formation there were far more bodies than there are now, and that collisions were common.
6. Limited information from meteorites and the Moon seems to suggest that most objects in the Solar System, including the Earth, formed about the same time – between 4 and 5 billion years ago. Extrapolation of decay times from radioactive elements suggests that these, and all heavy (i.e. heavier than iron) elements were formed in a supernova explosion some 8 billion years ago.

How the Solar System formed: Ideas in the mid 20th century


Black spot has been cleared of dust to form protoplanetary disk

The theory that developed out of these observations was that the planets were formed from the same dust and gas cloud that formed the Sun, the [protoplanetary disk](). The eight planets condensed around heavier 'seeds' because of gravitational effects, with the heavier elements sinking to their cores as molten iron and other elements. These surrounded by oxides and silicates of iron, magnesium and other elements, surrounded in turn by more volatile materials such as water, methane, carbon dioxide and ammonia and finally by hydrogen and helium. The process of the matter clumping together like this because of gravity is called planetary accretion.

The heat from the Sun and the solar wind blew away various amounts of these volatile materials from the four inner planets, the amount and composition of what was retained depending partly on the gravity (and therefore on the mass of the rocky core) and on temperature.

The outer four planets retained much more of their volatiles, and varying amounts of their hydrogen (Jupiter and Saturn in particular retained much because of their large mass and therefore gravity). The ability of the solar wind to remove hydrogen decreases further from the Sun.

Moons around the planets condensed from the same matter that formed the planets themselves, but retained less volatile content because of the lower gravity.

A planet was unable to form properly in the orbit of the asteroid belt because of the influence of Jupiter's gravity, and the asteroids are the 'rubble' of the planet that didn't form. Beyond the orbit of Neptune it was cold enough for relatively small rock masses to form nuclei for the condensation of volatiles, forming the Kuiper Belt and KBOs. The remains of the gas/dust cloud cooled and condensed much further out as cold, fluffy snowballs in the Oort Cloud. Because of the large distance from the centre of gravity, the further out an object the less likely it is to be pulled into the ecliptic. Occasionally, some of these condensed snowballs are disturbed enough for the Sun's miniscule (at this distance) gravity and falls towards the Sun as a comet.
The gravity of the eight major planets attracted much of the leftover material, 'cleaning up' the system and forming large impact craters. These are preserved on the Moon but not the Earth (because of the Earth's constantly changing surface). The rate of impact is now much lower.

Many aspects of this model, as a generalisation, are thought still to be correct. However, the discoveries made since the Moon landings and missions to explore other planets have called aspects into question and refined the model somewhat. Even more questions about the formation of planetary systems in general (as opposed to our particular Solar System) have arisen because improvements in telescope technology have allowed large planets around other stars to be observed. Some of these orbit far too closely to the star to fit with the above model. Our understanding of other planets (called exoplanets) is also greatly hampered by the fact that we cannot yet observe Earth-sized or smaller planets, or those a long distance out from their primary, around other stars. Therefore our sample of exoplanets is thought to be non-representative of planets in general.

1. Explain the following terms with respect to the Solar system

Rocky planet ....

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Gas giant ....

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Rocky moon..

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Icy moon ....

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Dwarf planet ....

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Kuiper belt ....

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Oort cloud ....

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Comet ....

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Asteroid belt ....

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Chondrite (rocky) meteorite ....

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Carbonaceous meteorite...

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Nickel-iron meteorite ....

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Ecliptic ....

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2. Why is Pluto no longer considered a true planet?

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3. Earth's Moon is thought to have formed by a very different mechanism from the moons of Mars or Jupiter. Explain.

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4. What is a protoplantetary disk?

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Further developments from space exploration and observations of exoplanets

The Moon missions:

Rocks brought back from the Moon show some interesting features. Much of the Moon is covered in regolith, dusty fragments blown out from impacts or condensed from rock vaporised in those impacts. However, the lunar missions brought back some 'true' rocks. Some of these are basalts, remarkably similar to those of Iceland or of the ocean depths (except utterly lacking in minerals which include water in their composition). They are thus likely to be formed by a similar mechanism i.e. partial melting of a material similar to the Earth's mantle. The overall density of the Moon suggests a composition similar to Earth's mantle.

If the Earth and the Moon were originally formed from the same part of the proto-system, one would expect a bigger variation in the Moon's composition and density, and a greater range of rocks at the surface. Alternatively, if the Moon were captured from elsewhere in the system one might expect more differences in chemical composition between the Moon and the Earth than is actually the case. Chemical evidence suggests that parts of the Moon and Earth have a similar origin. A major theory is that a Mars-sized planet collided with Earth, sending much of the mantle of proto-Earth and of itself into orbit. This orbiting matter gradually condensed into the Moon. The denser parts of the colliding planet, Thea, sank inside the Earth and continue to be part of our core and mantle. The material that formed the Moon continued to rain down on it for quite a time, melting parts of the surface to form plains of dark basalt.

A feature of this model is that it requires at least one other large wandering planet in the inner system, a substantial modification of the theory prior to this. Further evidence that there were quite a number of such bodies would emerge as we came to understand more about Mars and Venus.

Mars

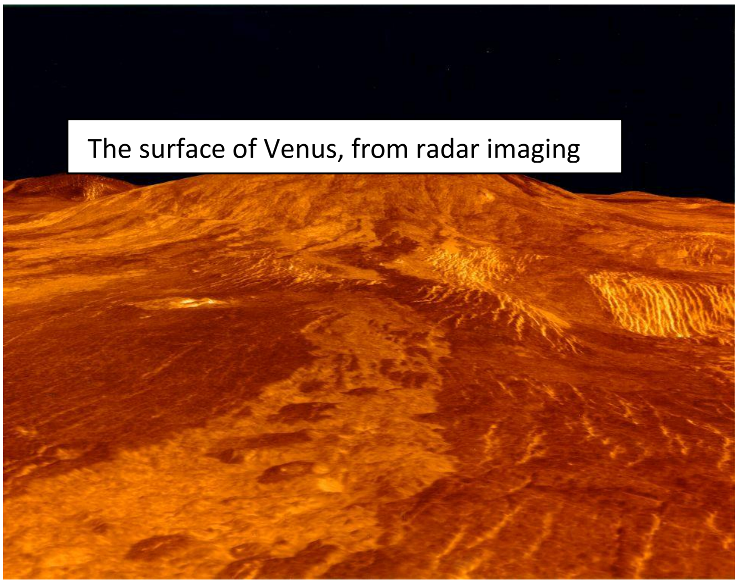
We now know substantially more about Mars than was known in the 20th century. Detailed mapping of its surface has revealed a particular feature – the fact that one hemisphere of Mars (the northern) is substantially lower in mean altitude than the other; were Mars a watery planet, this hemisphere would be almost entirely ocean.

A leading theory is that Mars has also been subject to a giant collision, and in fact may be the product of the merging of two smaller and similarly sized objects. Smaller, later impacts possibly threw material into orbit to become Mars' two moons (Phobos, the larger and nearer, and Deimos). Both these moons have unusually low density, but seem to be composed of rock (not ice). This suggests that they may be large piles of fairly loose rubble, held together by their own (weak) gravity. Phobos' orbits is so close to the planet that it orbits faster than Mars rotates, so seems to go 'backwards' in the sky (i.e. rises in the west and sets in the east). Seen from Mars' surface, it takes only about four hours to go across the sky. Computer models suggest it will either impact or break up in a few tens of millions of years' time.

Mars' smaller size meant that no true mantle convection could occur, and thus no plate tectonics. With comparatively little volcanism to renew its atmosphere, and weak gravity with which to retain it, most of Mars' atmosphere has been 'blown' off by the solar wind. The global cooling resulting from this lead to much of the remaining water being frozen into the subsoil, particularly near the poles. The present atmospheric pressure on Mars is usually too small for water ice to melt; instead, like dry ice, it mostly sublimes. Occasional flash floods of liquid water may occur where underground sources are breached (e.g. by impact) raising the local pressure and allowing liquid water to briefly exist before boiling away. Substantial quantities of frozen carbon dioxide exist at the poles because the cold temperature is usually below the solidus of carbon dioxide. This also sublimes but never melts.

Venus

In size and bulk composition Venus resembles Earth. However, it lacks a strong magnetic field, which on Earth protects us from much of the solar wind. This meant that methane and water in the upper atmosphere could be split into hydrogen and carbon dioxide, with the hydrogen being carried away in the solar wind. If any carbon cycle ever existed to lock up carbon on Venus, it died away fairly early in the planet's history. There is therefore a huge, thick atmosphere of carbon dioxide with a surface pressure equivalent to a kilometre deep in Earth's oceans. The runaway greenhouse effect of all this gas produces surface temperatures high enough to melt lead, despite the high albedo caused by the clouds of sulfuric acid.


The surface of Venus, from radar imaging

Towards the end of the 20th century, radar imaging produced the first 'maps' of the surface. These are fascinating.

There is considerable evidence for major impact events on Venus. Its rotation is very different from other planets, although this may result from tidal effects of the Sun on Venus' thick atmosphere.

Radar imagery of Venus' surface indicates many impact craters, despite the fact that the surface is relatively 'young'. Venus may have had impacts producing a satellite like Earth's – some of its rotation data suggests this; however, the satellite would have generated huge tides in the thick atmosphere and this would have gradually dragged the satellite in and destroyed it.

Venus has considerable evidence of volcanism. It appears that, without water to lower the melting point of crustal rocks and produce Earth style plate tectonics, a different process is at work. Venus mantle heats up until it is hot enough to melt and resurface much of the crust in a giant volcanic episode. The last of these seems to have happened between 400-600 million years ago. Whatever process is occurring in Venus' core, it does not produce the dynamo effect of Earth's core which produces our magnetosphere. Either the core is wholly liquid, or it is wholly solid; either would explain this. Only a probe robust enough to carry out seismic surveys on Venus will answer this question.

Mars, Earth and Venus therefore all produce considerable evidence for a very active early Solar System containing many planet-sized bodies which collided and merged. The present rocky inner planets seem to have emerged from this.

1. What evidence is there that the Moon and parts of the Earth have a common origin?.

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2. Why are there so many missions to Mars?

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3. Venus, Earth and Mars are 'triplets' – similar in origin and general composition but very different on their surface. Explain how they came to be so different.

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Exoplanets (Extrasolar Planets)

Although the existence of planets around other stars had long been thought likely, it was not until the discovery of a large planet in a 4 day orbit around the star 51 Pegasi in 1996 that they were actually observed (a planet around a pulsar had been discovered four years earlier, but 51 Pegasi b was the first observed around a main sequence star). As at April 2012, some 763 exoplanets have been discovered.

'Hot Jupiters' as these planetary types are termed, have highlighted the role of planetary migration (that is, movement of a planet to a different orbit) in planetary system formation. Models suggest there would not be enough matter that close to a star to form a planet of this size.

Current thinking about planet formation

The earlier model of planets forming by accretion of bodies formed in the protoplanetary nebula largely stands. However, it is now thought that there were originally a lot more of them than are present today. Protoplanets closer to their stars condense with far fewer volatiles, although they can (like Earth and Venus) regenerate atmospheres by the outgassing of volatiles, particularly during volcanism. There is a zone around a star (in our Solar System, just inside the orbit of Jupiter) where it is too hot for volatiles to condense.

The fact that the largest planet in our system formed where it has seems to be no accident. Jupiter formed close to the inner zone of where it was cold enough for volatiles to condense. Because this is where the greatest concentration of material would be found, it grew to be the largest planet in our system. Once formed, its gravity seems to have had a major effect on the other planets and some may have migrated to their present position. The distribution of the planets may be partly due to resonances in the orbital periods. However, there seems to be considerable variation in the way planets are distributed around stars, going on the limited data from exoplanets.

In our system, Pluto is a KBO which got pushed into a resonant orbit with Neptune (Neptune orbits exactly twice for one orbit of Pluto). This resonance explains why Pluto's orbit can cross Neptune's without them ever having collided. Neptune's major moon, Triton, is probably another KBO which got captured by Neptune's gravity.

The present arrangement of the Solar System cannot be modelled indefinitely into the future; it is chaotic. Some models suggest that future planetary migrations, particularly of the inner planets, may occur. We could therefore predict that there may be other configurations of planets possible in other systems.

Life

The set of circumstances which led to Earth being a planet capable of supporting life appear to be quite unusual. It needs to be a rocky planet with a fairly stable orbit, at a distance from the primary where formation of liquid water is possible. A large moon helps prevent wild changes in the axial tilt, which would likely cause much greater variation in climate and at least make it more difficult for complex life to evolve. Plate tectonic type volcanism helps 'top up' the atmosphere and provide areas of crust which are stable for long periods of time. Periodic resurfacing, as happens on Venus, or relatively little volcanism, as on Mars, would be very inimical to life. Plate tectonics does seem to need a particular distribution of matter within the planet.

This particular combination of circumstances should occur in other systems, but is presumably not a given in every system. Present data suggests that at least 60% of main sequence stars, at least from classes M through to B, should possess planets. Therefore there must be other planets out there similar to Earth in general characteristics, but they are likely to be not all that common. As to the other factors that lead to the development of life, and its evolution to our level of biological complexity, we simply do not have enough data at the moment to know. It should be remembered that for more than three-quarters of the time that life has been present on Earth, it was simple and mostly single celled. We are not presently sure how significant geological and cosmological events were in the development of complexity.

There is no scientific evidence that the evolution of self-aware intelligence as an adaptive mechanism has any sort of

biological inevitability to it. Our own evolution seems to be the result of a series of coincidences – for example, the meteor that wiped out the dinosaurs that lead to the rise of mammals; the formation of the Himalayas which dried out Africa at a time when our tree-dwelling ancestors had developed the beginnings of bipedalism and were thus ready to adapt by spreading into savannah woodland and so on. Perhaps one day we will have a better idea of just how significant (or not) these things are.

1. What are the main methods by which exoplanets are detected?

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2. What are some of the 'unexpected' things that have emerged from the exoplanets so far discovered?

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